New Directions in Kaon Physics

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Recent measurements of kaon decays provide new information about CKM unitarity, lepton universality, and discrete symmetries. KLOE-2, the proposed extension of the kaon physics program at Frascati, will extend the world data set on kaon decays and conduct interference measurements with neutral kaons. Meanwhile, the decays $K \to \pi\nu\bar{\nu}$ can be directly related to the CKM matrix elements with minimal theoretical uncertainty, and are the focus of a series of experiments. Several events of $K^+ \to \pi^+\nu\bar{\nu}$ have been observed to date; the goal of the NA62 experiment at CERN is to perform an $\mathcal{O}(100)$-event measurement in this channel. Initiatives in Japan—the E391a experiment at KEK, to become E14 at J-PARC—are focused on collecting a few $K_L \to \pi^0\nu\bar{\nu}$ events in a first step, while working towards an $\mathcal{O}(100)$-event measurement. Experiments capable of performing $\mathcal{O}(1000)$-event measurements in both channels have been discussed.

1. Current Trends in Kaon Physics

An abundance of new measurements of kaon decays are providing precision tests of the flavor sector of the Standard Model (SM). If the couplings of the W to quarks and leptons are indeed specified by a single gauge coupling, then the CKM matrix must be unitary for universality to be observed as the equivalence of the Fermi constant G_F as measured in muon decay and in hadron decays. The current results from the FlaviaNet Kaon Working Group [1] based on world data on V_{us} from $K_{\ell 3}$ decays and V_{us}/V_{ud} from $K_{\ell 2}$ decays (using recent lattice QCD results [2, 3] in either case), as well as on the world-average value of V_{ud} from $0^+ \to 0^+$ nuclear β decays [4], verify first-row CKM unitarity to within $1 - |V_{ud}|^2 - |V_{us}|^2 = 0.0002(7)$, giving the second most precise determination of G_F after that from muon decay. From dimensional arguments, this agreement can be said to constrain physics models mediated by new particles (Z' bosons, SUSY, technicolor) at mass scales of $\mathcal{O}(1$ TeV) at the loop level, or $\mathcal{O}(10$ TeV) at tree level [5].

$K_{\ell 2}$ decays are helicity suppressed. As a result, hypothetical new-physics contributions are potentially observable in the $K_{\mu 2}$ rate, such as a tree-level contribution from the H^+ in certain two-Higgs-doublet models (in analogy to the case of $B \to \tau\nu$; see Ref. 6), or contributions from right-handed quark currents [7]. However, evaluation of the rate in the SM is tricky; the uncertainty on f_K, the kaon decay constant, dominates $\Gamma_{\rm SM}(K_{\mu 2})$. FlaviaNet [1] performs a fit to the experimental data on $\Gamma(K_{\mu 2})/\Gamma(\pi_{\mu 2})$, V_{ud} from $0^+ \to 0^+$ decays, and V_{us} from $K_{\ell 3}$ decays, as well as the recent lattice QCD values for f_K/f_π and $f_+(0)$, to obtain a value for $R^2_{K\mu 2} \equiv \Gamma(K_{\mu 2})/\Gamma_{\rm SM}(K_{\mu 2})$ (the fit assumes first-row CKM unitarity as well). The result of this analysis, $R_{K\mu 2} = 1.004(7)$, can be used to exclude a region of the $\tan\beta$ vs. m_{H^+} parameter space that is not excluded by $B \to \tau\nu$ data.

Because of the strong helicity suppression of the K_{e2} decay, its rate is particularly sensitive to new-physics contributions. In minimal supersymmetric SM extensions (MSSM) with R parity, the H^+-mediated process with an effective $eH^+\nu_\tau$ coupling (dependent on the value of the mass insertion Δ_{13}) may add a lepton-flavor-violating contribution of as much as $\sim$1% to the K_{e2} rate, for $\tan\beta \sim 40$, $m_{H^+} \sim 500$ GeV, and $\Delta_{13} \sim 5 \times 10^{-4}$ [8, 9]. In addition, observable deviations of R_K from the SM value are expected in certain supersymmetric grand-unification models [10]. In the SM, the ratio $R_K = \Gamma(K_{e2})/\Gamma(K_{\mu 2})$ has been calculated with precision: $R_K^{\rm SM} = 2.477(1) \times 10^{-5}$ [11]. The 2007 FlaviaNet experimental average (including preliminary results from NA48 and KLOE) is $R_K = 2.457(32) \times 10^{-5}$ [1]. There is much interest in reducing the experimental uncertainty on R_K.

World data on K_S and K_L decay amplitudes and can be combined to to obtain refined values for the CP- and CPT-violation parameters $\mathrm{Re}\,\varepsilon$ and $\mathrm{Im}\,\delta$ using the Bell-Steinberger unitarity relation. Such an analysis was performed in 2001 by the CPLEAR collaboration [12]. Missing amplitude data for semileptonic K_S decays were supplied by KLOE measurements [13], and in 2006, KLOE performed an improved unitarity analysis [14]. At present, the uncertainties on the phases of the K_L-to-K_S amplitude ratios η_{+-} and η_{00} limit the precision of the unitarity analysis. Together with their recently announced final result for $\mathrm{Re}\,\varepsilon'/\varepsilon$ [15], KTeV quotes new measurements of the phase differences ϕ_ε and $\Delta\phi$ (updating the results in Ref. 16), each with precision matching that of the current PDG fit, allowing further improvements.

Interference techniques can provide measurements of the amplitude ratios and other parameters of the K_SK_L system, as well as a number of tests of quantum mechanics. At the Frascati ϕ factory, DAΦNE, K_SK_L pairs from ϕ decay are created in a pure $J^{PC} = 1^{--}$ quantum state. The relative decay time distribution for K_SK_L decays to final states f_1f_2 contains an interference term that oscillates like $\cos(\Delta m \Delta t - \phi_{12})$, where ϕ_{12} is the phase difference between the ampli-

tude ratios $\eta_{1,2}$ for K_L and K_S decays to each final state. For $f_1 = f_2 = \pi^+\pi^-$, $\phi_{12} = 0$, and no decays are expected with $\Delta t = 0$, reflecting the antisymmetry of the initial state contracted with the symmetry of the final state. KLOE does in fact observe a deficit of decays at small Δt, confirming this prediction of quantum mechanics. This observation can be quantified by multiplying the interference term in the fit function by $(1-\zeta)$, with the decoherence parameter $\zeta = 0$ in quantum mechanics. Working in the K_SK_L and $K^0\bar{K}^0$ bases, KLOE obtains the preliminary results $\zeta_{SL} = 0.009 \pm 0.022_{\rm stat}$ and $\zeta_{00} = (0.030 \pm 0.012_{\rm stat}) \times 10^{-6}$ [17]. With increased statistics, KLOE could perform a wide variety of interference measurements.

2. A Bridge to the Future: KLOE-2

As observed in the preceding section, new results in kaon physics continue to be announced by experiments such as KLOE, KTeV, and NA48. An extension of the KLOE program has been proposed [18, 19] to pursue new, higher-statistics measurements of many (if not all) of the observables discussed above.

The KLOE detector (Fig. 1) consists of a large ($r =$ 2 m) cylindrical drift chamber (DC), surrounded by a lead/scintillating-fiber electromagnetic calorimeter (EmC), and features several optimizations for studies of the K_SK_L system. For a review of the KLOE detector and physics program, see Ref. 20. Most KLOE data were taken in 2001–2002 and in 2004–2005, for a total integrated luminosity of 2.5 fb^{-1}, or equivalently, of 2.5×10^9 K_SK_L pairs produced.

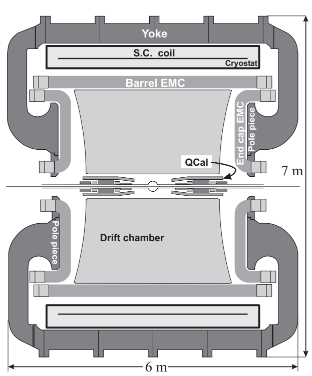

Figure 1: Cross section of the KLOE detector.

The DAΦNE design luminosity of 5×10^{32} cm^{-2} s^{-1} was never reached. The peak DAΦNE luminosity in 2005 running was about 1.5×10^{32} cm^{-2} s^{-1}. The proposal to continue the KLOE physics program stems from the prospect for a DAΦNE upgrade to result in a substantial luminosity increase. To obtain high luminosity at DAΦNE requires a small value of the vertical beta function at the interaction point, β_y^*. Because β_y^* can be made small only over a localized interval, this in turn requires a short beam-overlap region. The solution adopted for the DAΦNE upgrade [21] is the use of a beam-crossing angle that is large compared to the beam aspect ratio σ_x/σ_z. This also reduces the effects of the beam-beam interaction and parasitic collisions. An important element of the upgrade scheme is the use of a "crabbed-waist" sextupole correction, so that β_y is always at a minimum at the collision point, regardless of the horizontal betatron coordinate, x. This suppresses x-y betatron and synchrobetatron resonances. The crabbed-waist interaction region has generated much interest as a low-power-consumption solution for use at, for example, a super B factory or an upgraded LHC. At DAΦNE, the principle has been shown to work, and recently, a peak luminosity of 2.2×10^{32} cm^{-2} s^{-1} was obtained with beam currents somewhat lower than those used in 2004–2005 running [22]. DAΦNE performance continues to evolve rapidly.

Two phases of KLOE-2 running are envisioned [19]. The first phase ("Step 0") features minimal upgrades to the front-end electronics, DAQ, and online computing, as well as necessary modifications to the interaction region to work with new DAΦNE optics. Preparations will be complete in early 2009, and KLOE expects to collect about 5 fb^{-1} before shutting down in 2010 to install an inner tracker and new forward calorimeters (Fig. 2). During the second phase of running ("Step 1"), KLOE expects to collect a data set of 20 fb^{-1} or more.

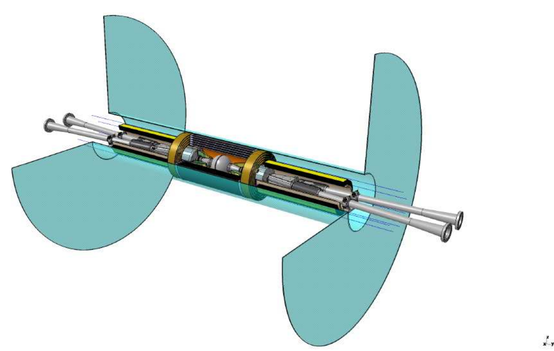

Figure 2: Design of the KLOE-2 interaction region, showing the new inner tracker and low-angle calorimeters.

The inner tracker will increase the acceptance for K_S and $K^\pm$ decay products and improve the vertex resolution for interferometry measurements. The goal is to improve the resolution on Δt, the time difference between K_S and K_L decays, from $\sim$0.9 τ_S (at present) to 0.25 τ_S. At the same time, the material budget for the tracker must be held to an absolute minimum. The solution chosen is a five-layer, cylindrical triple-GEM chamber with a total material burden of less than 0.02 X_0. A single-layer prototype has been constructed and is operational [23].

In addition, two new calorimeter systems will replace the current KLOE quadrupole calorimeters. To improve the photon-veto efficiency at small angle (for measurements of decays such as $K_S \to \gamma\gamma$), LYSO crystals will be placed in front of the new quadrupoles. LYSO combines high light yield with excellent timing resolution. To improve the hermeticity of the calorimeter system (e.g., to recognize $K_L \to 2\pi^0$ decays by photon veto), a lead/scintillating-tile calorimeter will be wrapped around the quadrupoles. The 5×5 cm^2 tiles are individually read out by WLS fiber coupled to silicon photomultipliers, providing high granularity [24].

Some highlights of the Step-0 physics program at KLOE-2 include measurements of the K_{e2} branching ratio (BR) to 0.5% and of the semileptonic K_S BRs to 0.3–0.5%, as well as a limit on BR($K_S \to 3\pi^0$) at the 10^{-8} level. The Step 1 upgrades will allow these measurements to be further improved upon, and will also open the door to studies of CP and CPT parameters in the $K_S K_L$ system and sensitive tests of quantum mechanics using kaon interferometry [25].

3. The Next Step: $K \to \pi\nu\bar{\nu}$

Four rare kaon decays provide information on the unitarity triangle, as illustrated in Fig. 3. These are

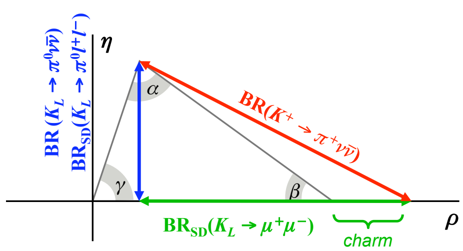

Figure 3: Determination of the unitarity triangle with rare kaon decays.

flavor-changing neutral current processes dominated by Z penguin and box diagrams. The $K \to \pi\nu\bar{\nu}$ decays proceed by the diagrams in Fig. 4. Their

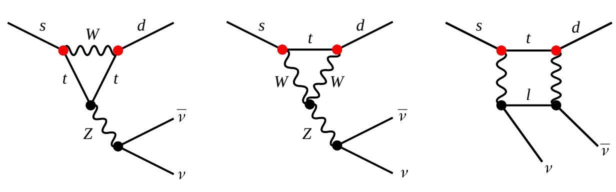

Figure 4: Diagrams contributing to the process $K \to \pi\nu\bar{\nu}$.

rates can be calculated with minimal intrinsic uncertainty in the SM, because there are no contributions from long-distance processes with intermediate photons, and because the hadronic matrix elements can be obtained from $K_{\ell 3}$ rate and form factor measurements [26]. Because of the hierarchy of the CKM matrix elements and the hard GIM suppression for these processes, the rate for $K^+ \to \pi^+\nu\bar{\nu}$ depends on the real and imaginary parts of λ_t, with some contribution from the real part of λ_c ($\lambda_q \equiv V_{qs}^* V_{qd}$). A recent evaluation of the SM decay rate gives BR $= (8.2 \pm 0.8) \times 10^{-11}$ [27]. The principal contributions to the error are the uncertainties on the current values of λ_t and m_c. With no parametric uncertainties, the error on the BR would be ~7%; the dominant non-parametric uncertainty is from non-perturbative effects in the charm-loop and long-distance contributions. (Recent work on the electroweak corrections to the charm contribution may reduce the non-parametric error [28–30].) The decay $K_L \to \pi^0\nu\bar{\nu}$ is CP violating; its rate expression depends on $\mathrm{Im}\,\lambda_\mathrm{t}$. In this case, there are no contributions to the uncertainty on the SM rate calculation from QCD corrections to the charm diagrams, and the prediction is particularly clean: BR $= (2.8 \pm 0.4) \times 10^{-11}$, with the uncertainties on λ_t and m_t as the principal error sources, and a non-parametric error of ~3% [26]. As pointed out in Ref. 31, assuming future experiments measure both BRs to 10%, the determination of the unitary triangle from kaon decays would approach the precision of that from B-meson decays. One hopes, however, to find signatures of new physics, which in many models are independent from those from B-meson observables. If there are indeed new sources of flavor-symmetry breaking at the TeV scale, such signatures may be dramatic. Although many proposed models have already been ruled out, an order-of-magnitude enhancement in BR($K_L \to \pi^0\nu\bar{\nu}$) is still possible in some MSSM [32, 33] and little-Higgs theories [34]. On the other hand, models incorporating minimal flavor violation scenario feature small (20–30%) deviations in the expected rate. (For a recent review with references, see Ref. 35.) Either way, the measurement of the $K \to \pi\nu\bar{\nu}$ BRs with 10% precision would provide fundamental insight into the mechanism for flavor-symmetry breaking, complementary to that to be obtained at the LHC. Experimentally, these measurements are extremely challenging.

3.1. $K^+ \to \pi^+\nu\bar{\nu}$

The main backgrounds to $K^+ \to \pi^+\nu\bar{\nu}$ are $K^+ \to \mu^+\nu$ (BR = 63%), where the muon is identified as a pion, and $K^+ \to \pi^+\pi^0$ (BR = 21%), with two lost photons. While these two-body decays can be kinematically recognized, they must be rejected at the level of 10^{-12}. In addition, there are backgrounds from radiative decays (such as $K^+ \to \mu^+\nu\gamma$ and $K^+ \to \pi^+\pi^0\gamma$) and $K_{\ell 3}$ and $K_{\ell 4}$ decays, as well as from events in which beam particles (π^+, K^+) are scattered or interact in detector materials. Excellent

charged-particle identification (especially μ/π separation) and photon vetoes are critical. Experimental searches may be conducted using either stopped kaons or decays in flight.

E787/949 at Brookhaven has actually measured this BR. The experiment makes use of a low-energy K^+ beam stopped in a scintillating-fiber target. A DC surrounding the target measures the momentum ($B = 1$ T) of outgoing charged particles. π^+ identification is obtained in the range stack surrounding the DC, which is instrumented with custom waveform digitizers capable of recording the decays at rest in the π-μ-e cascade. The experiment is surrounded by 4π of photon vetoes. The main sequence of E787 running was from 1995–1998. Two candidate events were recorded in a search window with the π^+ momentum above that for the $K^+ \to \pi^+\pi^0$ decay. The experiment was upgraded in 2001 and began running as E949 in 2002. Originally scheduled for 60 weeks of running, the experiment was terminated after just 12 weeks due to funding cuts. E949 found an additional candidate in the high momentum region, bringing the total number of candidates to three, with an expected background of about 0.4 events. The combined E787/E949 result for the high-momentum region is BR $= (1.47^{+1.30}_{-0.89}) \times 10^{-10}$ [36]. The collaboration has recently announced a new result for the search in the lower momentum region. Three additional events were found, with an expected background of about 0.9 events. Combining the data from both regions gives BR $= (1.73^{+1.15}_{-1.05}) \times 10^{-10}$, in accordance with (though somewhat higher than) the SM prediction [37].

The next step is NA62 (also known as P-326), a proposed decay-in-flight experiment at the CERN SPS [38]. The plan is to use elements of the NA48 apparatus to collect $\sim$100 $K^+ \to \pi^+\nu\bar{\nu}$ decays with a S/B ratio of 10:1 in two years of operation [38]. The experimental layout is illustrated in Fig. 5 [39]. The

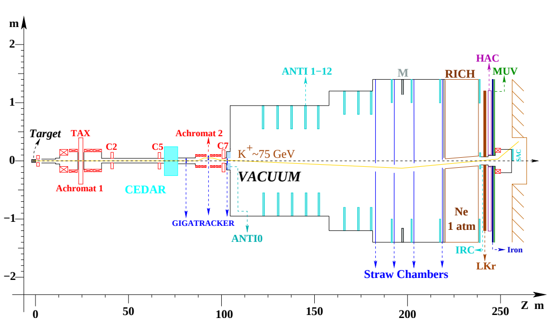

Figure 5: Schematic diagram of the NA62 experiment. Note the different vertical and horizontal scales.

experiment will make use of a 75-GeV unseparated positive secondary beam. The total beam rate is 800 MHz, providing $\sim$50 MHz of K^+'s. After beam momentum selection and collimation, kaons are identified in a differential Cerenkov counter (CEDAR) and the beam is tracked in the Gigatracker system, consisting of three thin silicon pixel detectors. The decay volume begins 102 m downstream of the production target. About 5 MHz of kaon decays are observed in the first 60 m of the 120-m long vacuum decay region. Large-angle photon vetoes are placed at 12 stations along the decay region and provide full coverage for decay photons with 8.5 mrad $< \theta <$ 50 mrad. The last 35 m of the decay region hosts a dipole spectrometer ($\Delta p_\perp = 270$ MeV) with four straw-tracker stations operated in vacuum. A ring-imaging Cerenkov counter (RICH) downstream of the decay volume provides μ/π separation. Downstream of the RICH, the NA48 liquid-krypton calorimeter (LKr) [40] is used to veto high-energy photons at small angle. Additional detectors further downstream extend the coverage and efficiency of the muon detection and photon-veto systems.

$K^+ \to \pi^+\pi^0$ decays must be rejected at the level of 10^{12}. Kinematic cuts on the K^+ and π^+ tracks provide a factor of 10^4 and ensure 40 GeV of electromagnetic energy in the photon vetoes; this energy must then be detected with an inefficiency of 10^{-8}. In $\sim$80% of the events, both photons enter the forward veto; in the remaining events, a hard photon enters the forward veto and a softer photon must be detected at large angle. Studies of $K^+ \to \pi^+\pi^0$ decays in NA48 data and tests conducted in 2006 with tagged photons from an e^- beam confirm that the LKr has an inefficiency of less than 10^{-5} for photons with $E_\gamma > 10$ GeV, providing the needed rejection for forward photons [39]. The large-angle vetoes must have an inefficiency of $\lesssim 10^{-4}$ for E_γ as low as 200 MeV. The plan is to construct the veto rings from lead-glass modules from the OPAL electromagnetic calorimeter barrel [41]. In a 2007 comparison of different technologies performed at Frascati, the lead-glass modules were shown to have 10^{-4} inefficiency for 200 MeV electrons [42].

The particle-identification systems must provide 10^7 μ rejection in π selection. A standard downstream muon detector provides a factor of 10^5; the additional rejection will come from a RICH situated upstream of the LKr [39]. In addition to providing μ suppression of better than 10^{-2} for $15 < p < 35$ GeV, the RICH must measure the track time with $\sigma_t = 100$ ps and provide the charged-particle trigger. The RICH is a Ne-filled (1 atm) tube, 18 m long by 2.8 m in diameter, with a through beam pipe and two inclined mirrors to image the Cerenkov ring on 2000 compact PMTs packed in an 18-mm hexagonal lattice. A full-length prototype with 100 PMTs was tested in 2007 and provided $\sigma_t = 75$ ps time resolution. A 400-PMT prototype will be tested in fall 2008.

NA62 received preliminary approval for R&D work by the CERN SPSC in 2006. In 2007, NA62 collected more than 100 000 K_{e2} decays with a subset of the NA48/2 apparatus; a result for BR(K_{e2}) with 0.5%

precision is expected soon [43]. Detector prototypes were tested in 2007 running. More tests are scheduled for fall 2008, and the experiment hopes to obtain final approval by the end of the year. This would allow construction and installation in 2009–2011. Data taking would begin in 2012.

3.2. $K_L \to \pi^0\nu\bar{\nu}$

The $K_L \to \pi^0\nu\bar{\nu}$ signature is the absence of any detector activity other that from the two photons from the π^0. All other K_L final states have at least two extra photons or two charged particles (except $K_L \to \gamma\gamma$, which is easy to reject kinematically). The main K_L background is from $K_L \to \pi^0\pi^0$ with two lost photons. A hermetic and highly-efficient photon-veto system (including detectors in the exit path of the neutral beam) is critical. Neutrons in the beam reacting with residual gas in the decay volume can also produce π^0s (and ηs), so the decay region must be kept under very high vacuum. The reconstruction of the π^0 is the only sharp kinematic constraint available, and in beamline experiments, it is usually used to reconstruct the decay vertex position. Any successful experiment must incorporate additional topological constraints by design, such as as a very small beam cross section ("pencil beam"), the measurement of the direction of incident photons, or the use of a microbunched beam to obtain time-of-flight constraints. (The latter two techniques were proposed for use in the KOPIO experiment [44], which would have run at Brookhaven but for which funding was cancelled in 2005.)

The first experiment dedicated to the search for $K_L \to \pi^0\nu\bar{\nu}$ is the E391a experiment at KEK [45–47]. The experiment makes use of a neutral secondary beam from the KEK PS, collimated into a pencil beam. The beam halo is suppressed to 10^{-4} at a radius of 4 cm. The K_L momentum distribution at the detector peaks at 2 GeV.

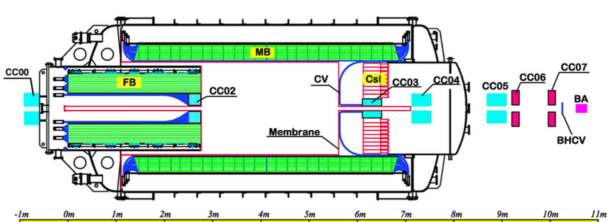

Figure 6: Schematic diagram of the E391a experiment.

The detector consists of two main regions: an upstream chamber, and a larger vessel containing the fiducial decay region, as schematically illustrated in Fig. 6. The upstream chamber is instrumented with the front barrel veto (FB), which rejects beam halo and secondaries from K_L decay upstream of the fiducial volume. The main barrel veto (MB) covers the walls of the larger vessel, and encloses the fiducial decay volume, which is evacuated to 10^{-7} mbar. Both the FB and MB vetoes are lead/scintillator sandwich counters. The main photon detector is an electromagnetic calorimeter at the downstream end of the decay volume, consisting of pure CsI crystals of $7 \times 7 \times 30$ cm^3. A plastic-scintillator hodoscope 50 cm upstream of the calorimeter acts as a charged-particle veto (CV). A number of ring-shaped "collar counters" (CC) extend the coverage of the photon-veto system to small angles; the BA counter is a dual-readout (scintillator/Cerenkov) sampling detector to veto photons leaving the experiment through the neutral-beam exit.

The experiment took data in three different runs in 2004–2005. Early results from the first run furnished the 90% CL limit BR $\leq 2.1 \times 10^{-7}$ [45], slightly improving on the previous limit from KTeV (obtained in the channel in which $\pi^0 \to e^+e^-\gamma$) [48]. E391a has recently released the results of their analysis of data from the second run [46]. Candidate $K_L \to \pi^0\nu\bar{\nu}$ events had two photons in the CsI and no activity elsewhere in the detector. The longitudinal coordinate z of the π^0 vertex was obtained by assuming $M(\gamma\gamma) = m_{\pi^0}$, with $M(\gamma\gamma)$ the two-photon invariant mass. A signal box was defined in the $p_\perp$ vs. z plane; the estimated number of background events in this box was 0.41 ± 0.11. No events were found, and an improved 90% CL limit BR $\leq 6.7 \times 10^{-8}$ was obtained. The data sample from the third run is comparable in statistics to that from the second run, but the collaboration expects analysis improvements to increase the signal acceptance.

Much of the E391a detector will next be moved to the J-PARC facility nearing completion at Tokai. Renamed E14, the next generation of the experiment aims to actually observe the $K_L \to \pi^0\nu\bar{\nu}$ decay [49]. The neutral beam will be selected at 16° from a 30-GeV primary proton beam from the J-PARC main ring, and transported along a 20-m beamline in the Hadron Hall. The new beam will feature a core-to-halo ratio of 10^{-5} (down from 10^{-4} in E391a) and a neutron to K_L ratio of 7 (down from 40). The momentum spectrum at the experiment is slightly softer, which decreases background levels from neutron interactions. Among the upgrades to the detector, one of the most significant is the replacement of the E391a CsI crystals with those from the KTeV calorimeter [16]. The latter are both longer (50 cm) and smaller in cross section (2.5×2.5 or 5×5 cm^2). The higher granularity of the calorimeter will reduce $\gamma\gamma$ merging, while the increased depth will reduce photon punch-through and longitudinal leakage. In particular, π^0s from neutron interactions in the upstream detectors contribute background when their z coordinates are misreconstructed because leakage causes one of the photon energies to be mismeasured. This effect was measured in E391a by placing an aluminum plate in

the beam to produce π^0s; MC studies suggest that this background source will be substantially reduced in E14. Various other upgrades are planned as well, including a new lead/aerogel in-beam downstream photon veto (styled after the KOPIO "catcher"), new veto counters around the beam holes, and new high-rate electronics.

Compared to E391a, E14 expects to benefit from tenfold increases in the K_L rate, signal acceptance, and running time. The beamline will be completed and surveyed by 2009. If all goes well, the experiment will have an engineering run in 2010, and a three-year physics run would begin in 2011. Three to seven signal events may be observed. Subject to further approvals, the three-year E14 run could be followed by a series of upgrades to the beamline and detector with the goal of pursuing an $\mathcal{O}(100)$-SM-event measurement.

An experiment somewhat similar in concept to E391a/E14 has been proposed at the IHEP 70 GeV synchrotron in Protvino [50, 51]. The KLOD experiment would use a a neutral beam extracted at large angle, with an n/K_L ratio of less than 10 and 10^8 K_L per pulse with a peak momentum of 10 GeV. The technical design report for the beamline is complete and R&D work on the detector is ongoing. The KLOD experiment would make use of some innovative, cost-contained technical solutions, particularly in the design of the vetoes. The main barrel veto uses shashlyk calorimeter modules, with 1 mm scintillator plates interleaved with 0.3 mm lead foils. The downstream calorimeter is a lead/scintillating-fiber calorimeter similar in concept to the KLOE EmC, with the fibers arranged in x-, u-, and v-views to allow shower tracking, providing additional constraints for the reconstruction of the π^0. (The KOPIO experiment would have used a preradiator in front of the downstream shashlyk calorimeter for shower tracking.) The in-beam photon veto is also a fiber calorimeter, with dual readout (clear and scintillating fibers) to separate electromagnetic and hadronic showers. The KLOD experiment has received scientific approval, but additional funding will be needed for construction and running.

3.3. More Distant Prospects

In 2007, because of expected delays in the timeline for the International Linear Collider (ILC), the construction of a high-intensity proton source at Fermilab was proposed as an interim project [52]. Project X calls for the construction of an 8 GeV linac with ILC beam parameters—essentially a 1:100 scale implementation of the planned ILC linac technology. The beam from the Project X linac would be accumulated in the existing Recycler Ring, providing up to 200 kW of fast- or slow-extracted 8-GeV proton beam for precision physics ($\mu \to e\gamma$, kaon physics, and other topics). Beam circulating in the Recycler could also be transferred to the Main Injector and accelerated to 120 GeV, providing 2.3 MW of fast-extracted beam for neutrino physics.

The high intensity of the 8-GeV Project X beam (200 kW corresponds to $\sim 2 \times 10^{14}$ ppp for a 1.4 s duty cycle) would potentially make $\mathcal{O}(1000)$-SM-event measurements of $K \to \pi\nu\bar{\nu}$ decays feasible. Experiments with both charged and neutral kaons have been discussed [53]. The $K^+ \to \pi^+\nu\bar{\nu}$ experiment would use stopped kaons and is similar in concept to E787/949. The kaon momentum in the secondary beam is 450 MeV, and a higher field in the central tracker (up to 3 T in the Project X experiment) makes for a more compact design with better momentum resolution. The range stack is much more finely segmented, and a homogeneous liquid-xenon photon veto detector is used in place of the sampling detectors in E787/949. The $K_L \to \pi^0\nu\bar{\nu}$ experiment would be conceptually similar to KOPIO. Like KOPIO, it would make use of a microbunched beam to allow event-by-event measurement of the momentum of the incident kaon by time of flight, as well as a preradiator to measure the angles of incidence of the photons from the π^0 on the downstream calorimeter. Unlike in KOPIO, which used a flat beam in order to increase the beam flux while maintaining geometrical constraint in at least one dimension, the high Project X intensity would allow the use of a tightly collimated and symmetrical beam. This not only provides good geometrical constraints; it also resolves certain technical challenges related to the mechanics of the KOPIO design.

Unfortunately, in its report on US particle physics priorities for the next ten years, the P5 subpanel of the Energy Department's High Energy Physics Advisory Panel, while recognizing the importance of the above measurements, recommended funding for the kaon physics program at Project X only in the hypothesis that funding levels for high-energy physics are doubled over the next ten years [54]. (The subpanel recommended in favor of construction of the Project X facility, as well as of other elements of the physics program.) While the chances of the Project-X kaon physics program being pursued as proposed are slim, it is perhaps encouraging to see that world interest in these measurements remains high, and that serious discussion of experiments capable of $\mathcal{O}(1000)$-SM-event measurements has started.

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